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Atmospheric dust under glacial and interglacial conditions

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Abstract. The uplift, transport and deposition of dust have been implemented in the LMDz AGCM. Simulations of atmospheric dust transport have been performed under present day (PD) and Last Glacial Maximum (LGM) conditions. For the PD climate the large-scale atmospheric dust transport as inferred from atmospheric measurements is reproduced. Increased dust amounts are simulated almost everywhere for the LGM climate, and the concentration of dust in Antarctic ice is increased as inferred from ice cores. The model simulates substantially increased dust concentrations in Greenland ice, however they are still lower than values reported from ice cores.

Introduction

Atmospherically transported dust is an important tracer of the atmospheric circulation. Results from polar ice cores reaching back into the last glaciation [*Greenland Ice Core Project members*, 1993; *Petit et al.*, 1981] show that the concentration of dust in the ice varies strongly and abruptly with climate. Mineral dust is thus a very sensitive tracer of either the circulation, the transport efficiency, the past dust sources, or a combination of these. Earlier attempts to simulate the atmospheric dust cycle of the LGM [*Joussaume*, 1993; *Genthon*, 1992] only resulted in minor increases in dust transport to high latitudes, despite their differences in the definition of dust sources. This is possibly because of deficiencies in the polar regions of the previous generation of GCMs. Simulations with simpler models [e.g. *Andersen and Ditlevsen*, 1998] of the meridional transport of dust pointed to expressed variations in transport efficiency between the different climates.

We here present a new 3-dimensional model of dust mobilization, transport and deposition. Assuming almost unchanged dust sources between the PD and LGM climates allows to investigate the changed transport features between the two climate states.

The Model

The atmospheric dust cycle has been implemented in the LMDz AGCM, a new version of the LMD 5.3 GCM. The AGCM was used with a regular grid with 64 points in longitude, 48 in latitude, and 15 vertical layers. The GCM has been used successfully for the simulation of the polar climates [*Krinner and Genthon*, 1998], although mostly with stretched grids.

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For this study we considered dust particles with a radius of 1 μm (the mean radius of long-range transported particles [e.g. *Prospero*, 1981]) and a density of 2650 kg m^{-3}. The mixing ratio of dust mobilized from the ground, c_0, is assumed to be proportional to the third power of the wind speed, u, of the lowest model level (10 m above the ground) [*Gillette*, 1981], i.e.

$$c_0 = Cu^3. \tag{1}$$

The scaling factor, $C = 26.5\ \mu\text{g kg(air)}^{-1}\ \text{s}^3\ \text{m}^{-3}$, was fixed by setting the present global annual dust production to 2000 Mt [*Duce*, 1994]. Dust production is inhibited by a soil moisture content in excess of 5 mm (the maximum water holding capacity of the ground being 15 cm) and by more than 1 cm of snow cover. Dust mobilization only takes place over deserts, as prescribed from a present day vegetation data base [*Matthews*, 1983].

The mixing of dust has been incorporated in the implicit boundary layer scheme of the GCM, the massflux scheme for convective processes has been modified to include passive tracers, and dust is advected with the Van Leer scheme I [*Hourdin and Armengaud*, 1997]. Dry deposition of dust occurs through 1) mixing in the boundary layer, and 2) gravitational fallout. Wet deposition takes place for large scale and convective precipitation, following *Genthon* [1992].

The model has been run for two years in the PD climate and the LGM climate, using the boundary conditions of the control run (PD) and the GL21RC (LGM) run of *Krinner and Genthon* [1998] respectively. The PD vegetation was re-used for the LGM simulation. Due to the lower sea level of the LGM several ocean grid points of the PD simulation turn into land for the LGM simulation. Extrapolation of the PD vegetation from nearest neighbor grid points with defined vegetation here resulted in several new land grid points, especially at high latitudes being defined as deserts.

In order to discern between the different sources of dust transported to the polar ice caps, the horizontal model grid was split into five latitudinal bands (Table 1). Dust mobilized from each of these areas was treated separately in the model.

Results for Present Day

The PD large-scale transport of dust is well simulated by the model, as may be seen by comparison with measured values (Figure 1a). In the GCM dust is mainly produced from north African and Arabian deserts, and the strong observed transport of dust across the tropical Atlantic Ocean [e.g. *Husar et al.*, 1997] is reproduced. The general features of the observed strong dust production and transport from Asian deserts are reproduced in the model. However absolute values, especially for the Chinese deserts are too low. Model values for the south tropical Atlantic Ocean and

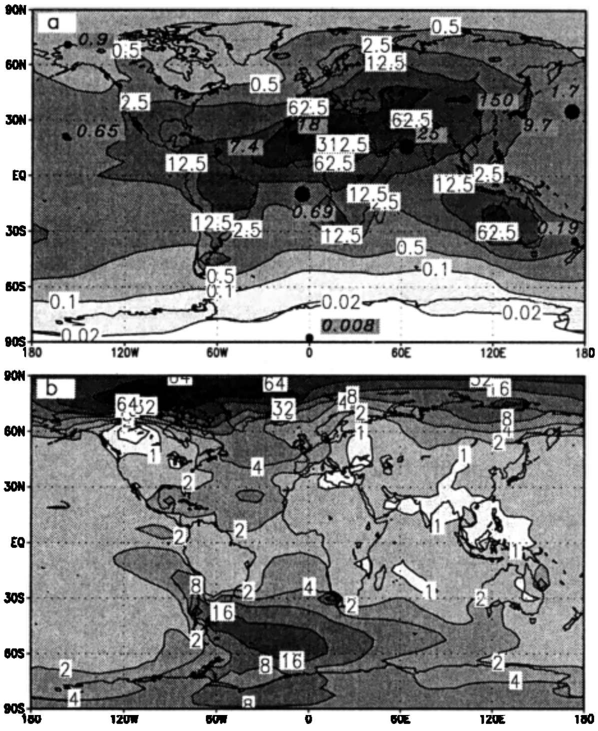

Figure 1. a) PD annually averaged atmospheric mixing ratio of dust [μg m^{-3} STP]. Numbers in italic correspond to measured values [*Duce,* 1994] and larger points indicate larger spatial averages. b) The ratio between the LGM and PD mixing ratio of dust. Both plots are for the lowest model level.

New Zealand are somewhat high and dust sources in Australia may be overestimated. This could be explained either by the fact that dust is in reality raised not only from pure deserts, or by the fact that not all deserts are equally strong dust sources [e.g. *Prospero,* 1981].

The concentration of dust in central Greenland ice in the PD simulation is 153 μg kg(water)$^{-1}$, about three times the measured value [*Hammer et al.,* 1985]. The largest part of the dust transported to Greenland in the model derives from NLL sources (Table 1). This is a rather constant contribution throughout the year, whereas the amount of NML dust increases considerably during the peak seasons (summer and spring), temporarily exceeding the NLL contribution. In the model dust is mainly transported to Greenland from the west (Figure 2a). The transport from the Eurasian continent occurs northwards over Siberia, along or across the Arctic Ocean, southwards over North Canada, across the Baffin Bay and towards Greenland. Dust from NML and NHL sources is mainly transported to Greenland in periods of strong baroclinic waves, with a strong northwards transport over the Eurasian continent, and relatively high northerly trajectories. Dust from NLL sources to a larger degree represents a high-level background aerosol, which is also transported to Greenland during periods of weak baroclinic activity and mostly zonal advection. The transport routes for dust from NML and NHL sources agree well with the results of back trajectory analyses [*Kahl et al.,* 1997]. Recent work on the dust isotopic composition and mineralogy moreover points to an Asian source of dust transported

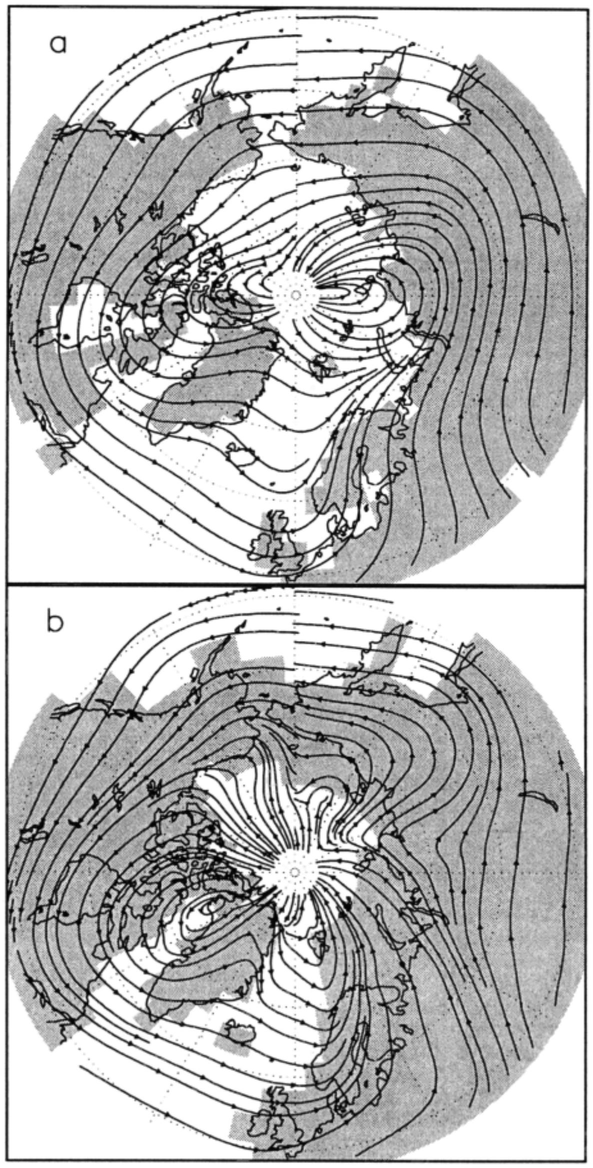

Figure 2. The vertically integrated annual mean dust flux to the Arctic. a) PD; b) LGM.

to Greenland for the PD [*Biscaye et al.,* 1997a], suggesting that the "background" of NLL dust is overestimated in the model.

For the Antarctic ice sheet the model simulates a dust concentration in the snow of 30 μg kg(water)$^{-1}$, at the high end of measured values [e.g. *Legrand et al.,* 1988]. The dust generally derives from SLL sources (Table 1), with a minor contribution from SHL (Patagonian) sources in the peak season (around November). The vertically integrated horizontal dust flux shows a very zonal advection of dust around the Antarctic continent (not shown here). Entrainment of dust to the Antarctic continent mainly occurs across the Ross Ice Shelf, and the transport appears strongest from Australia. The exact location of the SLL sources will however have to be investigated through further simulations, specifying different source areas.

Table 1. Dust Production from the Sources (Mt yr^{-1}) and Deposition to the Polar Ice Caps (mg m^{-2} yr^{-1})

			Production		Deposition	
Source area	Short	Location	PD	LGM	PD	LGM
Northern High Lat.	NHL	47°N-90°N	21.54	69.91	7.054	124.8
Northern Middle Lat.	NML	32°N-47°N	184.3	292.4	15.68	18.18
Northern Low Lat.	NLL	0°-32°N	1482	1864	42.41	30.85
Southern Low Lat.	SLL	40°S-0°	300.7	476.1	1.775	1.357
Southern High Lat.	SHL	90°S-40°S	5.010	11.48	0.138	1.242

Deposition is for Greenland in the northern hemisphere and Antarctica in the southern hemisphere.

Model-inferred Changes for the LGM

For the LGM simulation the dust production (Table 1) and the atmospheric dust content at low to middle latitudes (Figure 1b) are somewhat increased. As the sources of dust in this area are hardly different than for the PD simulation the increases can mainly be attributed to increased wind speeds over the source areas, generally drier conditions, and relatively lower washout of dust due to decreased precipitation.

The increase in dust deposition between the PD and LGM simulations resembles the pattern for the mixing ratio displayed in Figure 1b. The increase is generally higher in the Atlantic Ocean (a factor of ~3 north of the SHL sources) than for the other oceans, and higher for the southeastern (2-3) than for the western Pacific (1-2). *Rea* [1994] from deep sea sediment cores found slightly higher enhancement factors (3-5) for most low to middle latitude oceans. Unfortunately no dust deposition rates were reported for high latitudes, and we can thus not verify the large increases simulated at high latitudes e.g. off the Patagonian coast. These simulated increases are mostly due to enhanced local dust production.

As seen from Table 1 the simulated deposition flux of dust from NLL to Greenland and from SLL to Antarctica is actually lower for the LGM, than the PD. The total deposition flux of dust to the ice sheets is increased by a factor of 2 to 3 for Greenland and by a factor of ~1.5 for Antarctica (corresponding to concentration increases of 13 and 5) for the LGM. The factor found for the Antarctic ice agrees well with measurements [*Petit et al.*, 1981], but for Greenland the model underestimates the observed increase [*Hammer et al.*, 1985] by a factor of about 4.

For the LGM simulation dust transported to Greenland mainly derives from NHL sources. Preliminary tests splitting the NHL source area into an eastern (Asia) and a western (Greenland and North America) part indicate that the increases are mainly from small source areas simulated in northern Greenland. From these areas dust is transported very efficiently either directly southward, or southwestward, over the Baffin Bay and to the ice cap. The main transport route (Figure 2b) of dust from low to middle latitudes to Greenland during the LGM is through strong northwards advection over the central part of the Eurasian continent, across the Arctic Ocean, and around a very persistent low pressure system in the Baffin Bay.

The dust transported to Antarctica during the LGM derives to about equal amounts from SLL (a background level of ~60 μg kg(water)$^{-1}$) and SHL (reaching 200 μg kg(water)$^{-1}$ during the peak season) sources. The transport route of dust to the Antarctic ice sheet across, or east of the Weddell Sea is strongly enhanced for the LGM simulation, which allows for a very efficient transport of Patagonian dust to the Antarctic continent. This is consistent with a significant increase in cyclonic activity in the Weddell Sea [*Krinner and Genthon*, 1998].

As may be seen from Table 1 the increased dust amounts in polar ice in this study mostly derive from high latitude source areas, which are much enhanced during the LGM due to the drop in sea level, generally drier conditions, and higher wind speeds. The increased deposition on the polar ice caps of dust from low and middle latitudes is generally lower than the increased production in the corresponding source areas. This means that either the general transport efficiency of the atmosphere from low and middle latitudes to the ice caps is lower for the LGM, or the most favorable transport routes are altered to decrease transport from the PD dust source areas to the ice caps. Studies of the meridional transport efficiency of the glacial climate using simpler models point to an overall increased efficiency [e.g. *Andersen and Ditlevsen*, 1998], as the mid-latitude large scale turbulence increases and precipitation decreases.

Discussion and Conclusion

A model was used to investigate different aspects of the atmospheric dust cycle under glacial and interglacial climate conditions. Source distributions were unchanged, except for a few grid points being converted to land areas during the LGM due to the lower sea level.

For the PD simulation the general distribution of atmospheric dust is well simulated. However dust sources in northern Africa, Australia and on the Arabian Peninsula are overestimated. This deficiency might be overcome by 1) accounting for the different potential of dust production from the different deserts, e.g. through the inclusion of site-dependent threshold velocities, and 2) including the possibility of dust production from semi-arid areas. Both solutions would probably favor dust production from e.g. the Asian loess areas. A relatively lower level of dust from the low latitude deserts would ameliorate the simulated dust concentrations in Greenland and Antarctic ice. Significantly more advanced parametrizations of dust production than used here [*Marticorena and Bergametti*, 1995] require input data for the soil characteristics, which are currently not available on a global scale.

For the LGM the inclusion of semi-arid sources of dust, which would be highly dependent on soil moisture, would probably increase the dust mobilization from the ground considerably outside the main desert areas. Inclusion of more realistic boundary conditions for the dust mobilization (e.g. a more realistic vegetation data base) could also improve the LGM dust cycle. However as the model results may be very sensitive to boundary conditions, which are quite uncertain for previous climates we here preferred to investigate the LGM dust cycle while maintaining the present vegetation.

At high latitudes the model elucidates the transport of dust from new sources relatively close to the ice caps during the glacial period. The increased sources of dust in Patagonia agree with the source areas for LGM dust determined from Antarctic ice cores [*Grousset et al.*, 1992]. The simulated northern Greenland sources of dust in Greenland ice for the LGM do not agree with investigations determining Asian desert sources [*Biscaye et al.* 1997b]. The simulations show the different ability of the atmosphere to transport dust under the glacial climate. The mean meridional transport efficiency from low and middle latitude sources to the high latitudes does not increase to match the observed much larger deposition on the polar ice sheets. Therefore, either the low and middle latitude dust production at the LGM must have been much larger than accounted for in the model, or new sources must have developed at areas more favorable for transport to the polar areas. These areas appear to be situated at relatively high latitudes.

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